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TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ES-1

1.0 INTRODUCTION 1
1.1 BACKGROUND 1
1.2 OBJECTIVE OF THE DEMONSTRATION 2
1.3 REGULATORY DRIVERS 2

2.0 TECHNOLOGY DESCRIPTION 3
2.1 TECHNOLOGY/METHODOLOGY OVERVIEW 3
2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY 5

3.0 PERFORMANCE OBJECTIVES 7
3.1 PRIMARY ENERGY AND COST 7
3.2 CO_2 EMISSIONS AND COMFORT 8
3.3 INSTALLATION AND MAINTENANCE 9

4.0 SITE DESCRIPTION 11
4.1 FACILITY/SITE LOCATION AND OPERATIONS 11
4.2 FACILITY/SITE CONDITIONS 12

5.0 TEST DESIGN 15
5.1 CONCEPTUAL TEST DESIGN 15
5.2 BASELINE CHARACTERIZATION 15
5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS 16
5.4 OPERATIONAL TESTING 18
5.5 SAMPLING PROTOCOL 19
5.6 SAMPLING RESULTS 19

6.0 PERFORMANCE ASSESSMENT 23
6.1 PRIMARY ENERGY AND COST 23
6.2 CO_2 EMISSIONS AND COMFORT 25
6.3 INSTALLATION AND MAINTENANCE 25
6.4 SEASONAL PERFORMANCE RATINGS 26
6.4.1 Simulation Results 26
6.4.2 Experimental Improvement 26

7.0 COST ASSESSMENT 29
7.1 COST MODEL 29
7.2 COST DRIVERS 30
7.3 COST ANALYSIS AND COMPARISON 31

TABLE OF CONTENTS (continued)

Page

8.0 IMPLEMENTATION ISSUES 33
8.1 RETURNING OIL 33
8.2 LIQUID FLOODING 33
8.3 SUBCOOLING 34
8.4 SYSTEM CONTROLS 34
8.5 SUMMARY 34

9.0 REFERENCES 37

APPENDIX A POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. 2-Stage cold climate heat pump with economizing. 4
Figure 2. Map between West Lafayette and Camp Atterbury. 11
Figure 3. Barracks multi-purpose building at CAJMTC. 12
Figure 4. CAJMTC barrack blueprint. 12
Figure 5. Temperature profile. 13
Figure 6. Building 114 operations. 14
Figure 7. General experimentation plan. 15
Figure 8. Mechanical housing installed at CAJMTC. 16
Figure 9. Building integration. 17
Figure 10. Control strategy overview. 18
Figure 11. Data set 7 – room air temperatures. 22
Figure 12. Data set 7 – energy consumption of heat pump and furnace 22
Figure 13. Experimentally adjusted TRNSYS model – monthly CCHP electric consumption and heating COP. 27
Figure 14. Unico projections for performance of commercialized CCHP system. 30

LIST OF TABLES

Page

Table 1. Performance objectives. 7
Table 2. Gantt chart of CCHP field demonstration. 18
Table 3. Performance objective sampling. 19
Table 4. Summary of CCHP test interval. 20
Table 5. Building 114 results for energy, cost, and emissions. 24
Table 6. Building 113 results for energy, cost, and emissions. 24
Table 7. Condenser sales for 2011. 29
Table 8. Heat cost comparison. 32

ACRONYMS AND ABBREVIATIONS

AHRI	Air Conditioning, Heating and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BICE	Board on Infrastructure and the Constructed Environment
BTU	British Thermal Unit
CAJMTC	Camp Atterbury Joint Maneuver Training Center
ccf	100 cubic feet
CCHP	cold climate heat pump
CO_2	carbon dioxide
COP	coefficient of performance
COV	change of value
CRN	Cooperative Research Network
DoD	U.S. Department of Defense
DOE	Department of Energy
DX	direct expansion
EC	electrical conductivity
EES	Engineering Equation Solver
EF	water temperature
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
eQUEST	QUick Energy Simulation Tool
ESTCP	Environmental Security Technology Certification Program
ft^2	square feet
GSA	General Services Administration
HSPF	heating seasonal performance factor
HVAC	heating, cooling, and air conditioning
kBTU	Kilo British Thermal Units
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
NATE	North American Technician Excellence
NGF	natural gas furnace
NRECA	National Rural Electric Cooperative Association
PID	proportional–integral derivative

ACRONYMS AND ABBREVIATIONS (continued)

ROI	return-on-investment
RPM	revolutions per minute
SCF	standard cubic feet
SEER	seasonal energy efficiency ratio
SH	superheated
TMY	Typical Meteorological Year
TRNSYS	Transient Systems Simulation Program

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EXECUTIVE SUMMARY

The university/industry team of Purdue University, Trane, Emerson Climate Technologies, Danfoss, and Automated Logic Corporation of Indiana, demonstrated a new air-source heat pump technology that was optimized for colder climates. The technology has significant potential to reduce the primary energy used for heating small commercial or residential buildings and expand the range of air-source heat pumps to Department of Defense (DoD) facilities in the northern half of the U.S. Cold Climate Heat Pumps (CCHP) are less expensive to operate than an electric furnace and are cost competitive with fossil fuel sources of heat, even though the cost for natural gas is very low at this point in time. CCHP technology also has the potential for reducing greenhouse gas emissions because they are powered by electricity that could come from renewable energy.

The field demonstration was conducted at the Camp Atterbury Joint Maneuver Training Center (CAJMTC) in Edinburgh, Indiana, a small town located about 1 hour south of Indianapolis. Two barracks were selected for the test because they are typical for the small to medium size buildings encountered on military bases. Each building was approximately 6000 square feet (ft^2) and constructed of cinderblocks. Even though the barracks were roughly 50 years old they had recently been updated with insulation, a sheet metal roof, and a modern central heating, cooling, and air conditioning (HVAC) system. Both buildings had two zones for heating and cooling, which allowed for a direct comparison of CCHP technology to a modern gas furnace. The buildings were modified so that one zone used the cold climate heat pump and the other zone used its original modern central HVAC system. Both zones were instrumented so that energy consumption and comfort could be evaluated using a web-based control platform.

The key finding from this field demonstration was that the CCHP reduced the primary energy for heating by 19% as compared to the gas furnace. Although the energy savings was substantial, this did not meet the success criteria of 25% that was established at the start of the project. Cost savings and reductions in emissions can be computed directly from the energy savings. The operating cost of the CCHP was approximately the same as the gas furnace, which also did not meet the success criteria of 15% cost savings that was established at the start of the project. The field demonstration did meet the target for reductions in carbon dioxide (CO_2) emissions by achieving a 19% reduction as compared to the success criteria of 15%. The project was successful in terms of meeting other performance objectives for comfort, ease of installation, and maintenance. This was the first full scale field demonstration of CCHP technology and thus it is not surprising that the university/industry team encountered several challenges during testing. The implementation issues were mostly resolved during the course of the project, but included managing the flow of return oil to the compressors, flooding of the compressors with liquid refrigerant, and maintaining an appropriate level of subcooling at the condenser outlet. The refinement of control algorithms used to manage the operation of multiple compressors, a variable speed drive for the high stage compressor, and expansion valves for modulating refrigerant flow were essential for correcting problems and improving operation.

The field demonstration as a whole was very successful. The CCHP technology is being further developed and commercialized in partnership with Unico, Inc. of St. Louis, Missouri. The units used in this demonstration will be partially decommissioned to allow for future use of the

demonstration site. There is significant potential for improvements in performance and ultimately delivering a new HVAC technology that will help the DoD meet its energy reduction goals.

1.0 INTRODUCTION

The university/industry team of Purdue University, Trane, Emerson Climate Technologies, Danfoss, and Automated Logic Corporation of Indiana, demonstrated a new air-source heat pump technology that is optimized for colder climates with comparisons made to a natural gas furnace. The technology has significant potential to reduce the primary energy used for heating small commercial or residential buildings and expand the range of air-source heat pumps to Department of Defense (DoD) facilities in the northern half of the U.S. Additionally, the reduction in primary energy has the ability to reduce carbon dioxide (CO_2) emissions and fossil fuel consumption of buildings to satisfy goals of federal regulations on DoD facilities.

1.1 BACKGROUND

The building sector in the U.S. accounted for 41% of primary energy consumption in 2010 and 40% of the country's CO_2 emissions in 2009 (Department of Energy [DOE], 2011). The energy challenge is particularly acute for buildings in colder climates that have a longer heating season. Heating is by far the biggest consumer of energy, accounting for as much as 60% of the energy used in buildings located in cold climates. The problems with cold climate heating become even more significant when climate change considerations are factored in. The Alliance to Save Energy reports that 63% of households use fossil fuels to heat their homes. All combustion-based heat sources (oil, gas, coal, wood, etc.) add CO_2 to the environment. A heat pump uses electricity that could be produced using renewable methods that eliminate or greatly reduce CO_2 emissions.

Heat pumps have advantages over other heating technologies. They can provide for example, three or more units of heating while using only one unit of power input. Heat pumps can also supply both heating and cooling to a building. This combination reduces the amount of equipment, installation, and maintenance required. Additionally, a heat pump only requires electricity. This enables the utilization of renewable methods to produce electricity that eliminate or greatly reduce CO_2 emissions.

Both ground and air-source are two heat pump technologies available to residential and small commercial buildings. However, ground-source heat pumps are unattractive due to their high installation costs from drilling. Current air-source heat pumps installed in DoD facilities often require a supplemental source of heat when ambient conditions are below 25EF (-4EC). The supplementary source of heat is generally supplied by electric resistance, which is highly inefficient at approximately 1/3 the efficiency of the typical heat pump, or a natural gas/propane furnace. The need for supplementary heat is not attractive to facility managers because of increased cost and maintenance. Supplementary heating sources also diminish the energy, operating, and CO_2 emission savings from utilizing air-source heat pump technologies. A cold climate heat pump (CCHP) would be able to provide the required heating for most of the winter months due to its ability to have a modulating output. The result is less resistance heating operation for defrost and extreme ambient conditions. The benefits are lower operating costs, energy consumption, CO_2 emissions, and the cycle can reverse to provide cooling.

1.2 OBJECTIVE OF THE DEMONSTRATION

Six performance objectives were established to evaluate the technology when compared to a natural gas furnace: reductions of primary energy by 25 percent, heating costs by 10 percent and CO_2 emissions by 15 percent; compliance with American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 55 for comfort; ease of installation; and maintenance.

The comfort, installation, and maintenance performance objectives were met during the field demonstration. The CO_2 reductions surpassed the success criteria of 15 percent with a calculated reduction of 19 percent. The cost reduction was not satisfied because only a break-even difference was reached when using residential utility rates. The primary energy reduction was found to be 19 percent, which did not surpass the success criteria of 25 percent.

1.3 REGULATORY DRIVERS

The development and deployment of a CCHP supports a number of mandates to improve the efficiency of federal buildings, including buildings operated by the DoD:

- Executive Order 13514 "Federal Leadership in Environmental, Energy, and Economic Performance" that was signed by President Obama in October of 2009. This is the latest of several Executive Orders that include mandatory energy reductions for federal buildings. One overarching goal is achieving net-zero-energy buildings by 2030. This effort is largely managed by the General Services Administration's (GSA) Office of Federal High-Performance Green Buildings.
- The CCHP supports goals of the Energy Independence and Security Act of 2007. Section 315 specifically discusses "Improved Energy Efficiency for Appliances and Buildings in Cold Climates." This section calls for improved efficiency of mechanical systems as well as an increase of renewable resource usage. Current heating technologies in cold climates are challenged to operate from renewable resources. A CCHP is a versatile technology and would be able to operate off of electricity generated by wind, hydro, and solar renewable energy.
- The Board on Infrastructure and the Constructed Environment (BICE) of the National Academies studied the possibility of high performance federal facilities. Their report noted the abundance of opportunities to increase the performance of existing facilities. CCHPs would be one possible strategy for helping achieve high performance federal buildings.
- After federal energy legislation was passed in 2005 and 2007, the DoD developed its own Energy Security Initiatives. One component of the strategic plan is to create more efficient facilities. The DoD Energy Security Initiatives stated that 25% of the energy used by the DoD is consumed by buildings. This mandates that DoD installations reduce their energy consumption by 3% per year through 2015. A fully commercialized and widely deployed CCHP could help contribute to that goal.

2.0 TECHNOLOGY DESCRIPTION

A technology assessment conducted in 2002 for the DOE Building Technologies Program identified “cold climate heat pumps” as one of the top technologies with the potential for significantly reducing primary energy use in buildings (Roth, 2002). The report acknowledges that CCHPs are not the cheapest option in all situations. Heating using fossil fuels can sometimes be less expensive. The argument for CCHPs is easy to make when fossil fuel alternatives are not readily available. In these situations, a CCHP is clearly superior to a system that uses electric resistance for heat. The case for CCHPs becomes even more compelling when the negative impacts of increased global warming emissions are considered, due to the combustion of fossil fuels for heating.

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

An air source heat pump uses electricity to drive a vapor compression cycle to provide efficient heating or cooling to a building. The limitation of conventional heat pump designs is that the operational efficiency coefficient of performance (COP) of a conventional single stage heat pump declines at ambient temperatures below -4°C (25°F). Reducing the heating COP below a value of 2 means the heat pump is producing less than two units of heating per one unit of electricity input. As a reference, electric resistance heaters have a COP of 1 at best, providing one unit of heat for every unit of electricity. In addition, at -4°C conventional heat pumps can’t produce 10 kilowatts (kW) of heating and thus in many applications could not provide a comfortable environment. Therefore, there is great potential to expand the use of heat pumps if they can be designed for use in colder climates.

A CCHP differs from conventional heat pump designs with the addition of a compressor and a heat exchanger (economizer) as shown in Figure 1. It has two compressors connected in series to pressurize a low pressure superheated (SH) vapor refrigerant to a high pressure, and thus reaching a high temperature. The return air from the building absorbs energy in the form of heat from the highly pressurized refrigerant and then condenses the refrigerant to a subcooled liquid. This subcooled liquid is then separated into two streams. One stream of the liquid refrigerant enters the economizer to be subcooled further (as discussed in Section 8.3) and afterwards undergoes a rapid pressure drop via an expansion value causing a decrease in the temperature of the refrigerant.

After leaving the expansion valve, the low temperature refrigerant enters the outdoor heat exchanger. The outdoor heat exchanger causes the refrigerant to absorb heat from the relatively warmer outdoor air and evaporate until reaching a SH vapor. The low pressure refrigerant, SH vapor is then sucked into the compressor to be compressed and the cycle repeats. The second stream of the liquid refrigerant previously noted, goes through a secondary expansion value before entering the other side of the economizer.

The second stream is now able to provide additional subcooling due to its lower temperature relative to the refrigerant on the other side of the economizer. The cooling of the other stream leads to the heating of this refrigerant stream. The heated refrigerant is injected into a mixing chamber between the two compressors. The injection leads to a gain in performance of the system through the cooling of the discharge vapor of the low stage compressor.

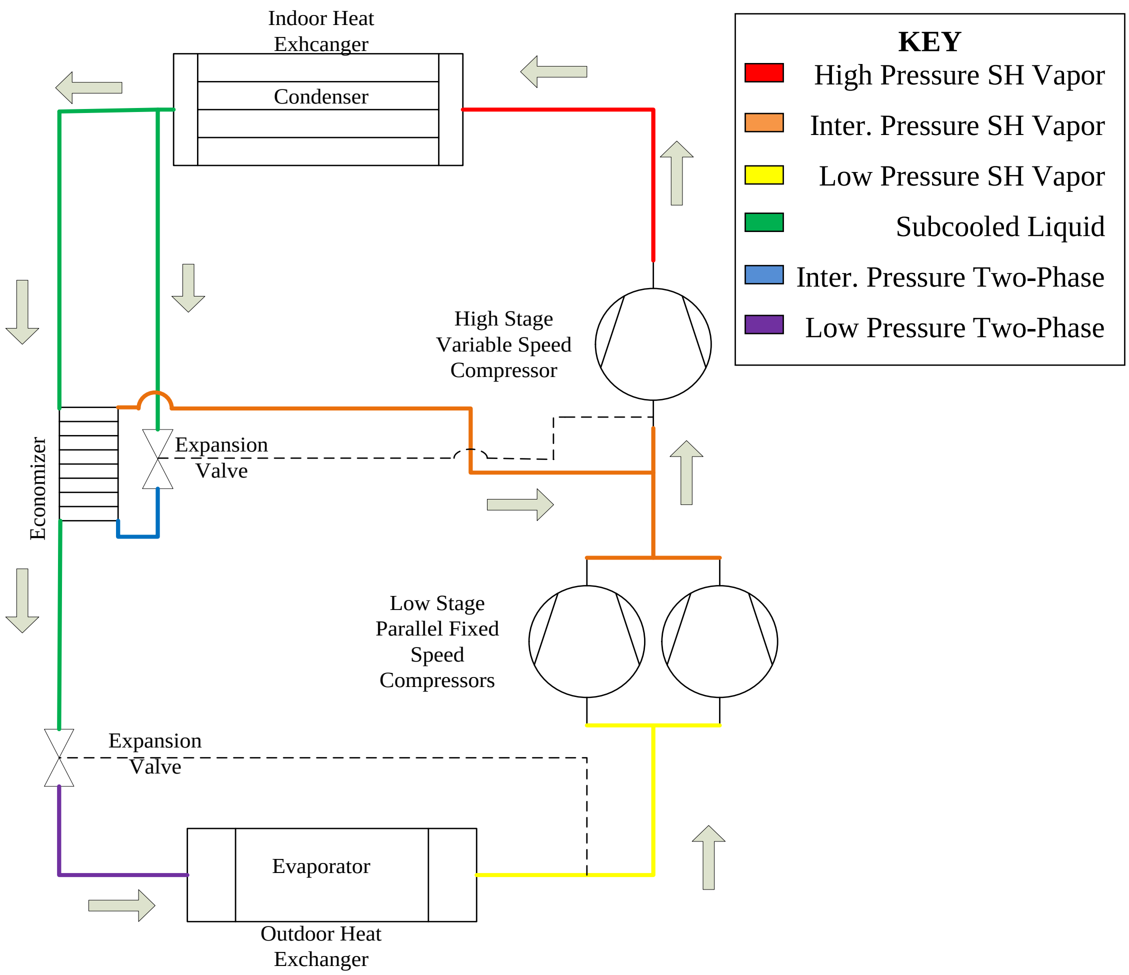

Figure 1. 2-Stage cold climate heat pump with economizing.

Implementing a four-way valve simply switches the condensing and evaporation locations. Heat pumps are equipped with this valve so the indoor heat exchanger can provide heating and air conditioning. During the heating mode described above, the condensing heat exchanger is inside while evaporation occurs outside. The simple change of the condensing/evaporating locations allows the heat pump to provide air conditioning or heating to the building.

Purdue University has been involved in the development and testing of CCHP technology for approximately 10 years. A prototype air-source two-stage heat pump that was optimized for heating loads in colder climates was constructed and successfully tested in the Ray W. Herrick Laboratories at Purdue University in West Lafayette, Indiana, starting in 2004. The equipment was tested in psychrometric chambers for ambient temperatures as low as -27°C (-17°F). In 2010, two U.S. patents (#7,654,104 and #7,810,353) were issued for the innovative control strategy and mechanical platform. This prior work was the basis for the 2010 proposal to the Environmental Security Technology Certification Program (ESTCP).

Early in the project a building energy model was created to establish the building's heating and cooling demand, and thus the overall required capacity of the CCHP. Several types of models with varying levels of sophistication were ultimately used, but the starting point was a relatively simple building energy model, eQUEST (QUick Energy Simulation Tool), from the DOE. The program uses second generation Typical Meteorological Year (TMY2) weather data and details of the building construction to simulate heating and cooling loads on an hourly basis over an entire year. The eQUEST model calculated that the maximum building heating load was roughly 65 Kilo British Thermal Units (kBTU)/hour (19 kW) at an outdoor temperature of -4°F (-20°C). In order to eliminate the amount of electric resistance heating needed as a back-up, this maximum heating load was selected as the design point for sizing the CCHP.

The outdoor design temperature is not arbitrary, but is an estimate of the coldest weather conditions that can be reasonably expected at Camp Atterbury. This 65 kBTU/hour heating value is significantly smaller than the 100 kBTU/hour (29 kW) rating of the gas furnace that was already installed in the building, but this type of oversizing is a routine part of military specifications for heating, cooling, and air conditioning (HVAC) equipment in buildings. Additional information on the building energy modeling can be obtained from Menzi et al., 2013.

The next phase of the design was the development of a heat pump model to evaluate and select individual components of the heat pump system. The heat pump simulation is necessary to verify that the CCHP has adequate capacity over the entire heating season for the field demonstration site. Detailed information about the heat transfer and flow characteristics of compressors and heat exchangers were the key elements of this model. This information was loaded into a computer program developed using Engineering Equation Solver (EES). Additional information on the heat pump modeling can be obtained from Caskey et al. (2012a) and Caskey et al. (2012b). The different operating modes are achieved by varying the compressor speed and the number of compressors. By varying its speed, the single stage (one compressor) mode is satisfactory for meeting the building heating load for a range of warmer outdoor temperatures. The two stage (two compressor) mode becomes necessary at ambient temperatures below about 7°F (-14°C).

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

The CCHP system can outperform all combustion-based heating sources in terms of energy efficiency. The best an oil, gas, or electric furnace can hope to achieve is something less than 100% energy conversion efficiency for the first and second law of thermodynamics. Basic thermodynamics shows that a heat pump cycle will deliver at least two or three times as much heat per unit of energy input. Using low stage and high stage compressors allows the CCHP to achieve an acceptable COP of around 3 during air conditioning and mild winters. This technology is driven electrically, so it is also compatible with renewable sources such as solar or wind. Additionally, the CCHP is operational at ambient temperatures far below air-source heat pump technology.

The CCHP should reduce the primary energy use for heating a small commercial building or an individual home by at least 10%. The first cost of this system will be higher than combustion

furnaces, but is estimated to yield a payback on the order of 5 to 6 years. The payback would be even shorter in areas where incentives are in place to encourage more heat pump installations. This could occur in locations where combustion-based heating (gas, oil, or propane) is not widely available. There exist other situations where geologic conditions, space constraints, or other environmental factors preclude the use of geothermal heat pumps. In these situations, a cold climate air source heat pump is vastly superior to other alternatives (e.g. electric heating).

A CCHP has the potential for complications because it is a new technology. The possibility exists that one stage of the two stage heat pump can have premature compressor failure if the lubricating oil migrates over time to the other compressor; causing it to run dry and seize. Satisfactory operation can be achieved using additional equipment, such as an oil separator and additional electric valves. Other options include turning off the compressors after a certain runtime for a required oil equalization time. These methods lead either to increased investment costs or a slight decrease of performance.

Another potential concern is the freezing of the outdoor coil during cold weather. This can be eliminated during the design of the outdoor coil. Designing around the drainage of water can reduce the accumulation of frost by optimizing the heat exchanger geometry and the air flow over the evaporator. Once frosting of the coils occurs, silent defrosting could be implemented, closing one or two circuits of the heat exchanger at a time. Closing the circuits allows an increase in temperature on the surface of the respective circuit and in turn melts the accumulated frost. Use of this technique will increase performance of the CCHP. It should be noted that currently only one expansion valve on the market can perform silent defrosting. Electric resistance heating is also an option in extreme situations.

The CCHP utilizes multiple compressors, economizing, and a control strategy that is not found with conventional heat pumps. Due to the extra equipment required in the CCHP design, the initial cost of the CCHP will be higher than most heating methods. The additional components create a potential to have higher maintenance costs through degradation and failure. One possible tradeoff is the elimination of oil management equipment to reduce the initial cost. The reduced initial cost would be a tradeoff by reducing performance resulting from the need of shut down to prevent compressor failure due to oil migration. Additional considerations would need to be made with this elimination. The projected savings from operating a CCHP over other heating equipment is expected to overcome these cost limitations.

New technologies have the potential to require an acceptance period for maintenance staff and facility managers. The CCHP controls should not present any significant barriers to personnel operating the new technology. Simple instructions on start-up and shut-down operations should eliminate this issue. The maintenance of the additional components and controls may require technicians who are performing maintenance and installation on the CCHP to attend training and education prior to corrective actions. The performance of the CCHP needs to be evaluated over many months to validate its benefits. Management may desire concrete results of expected performance before wide deployment.

3.0 PERFORMANCE OBJECTIVES

Six performance objectives for the CCHP field demonstration are listed in Table 1. Both quantitative and qualitative performance objectives are listed in the far left column. The metrics, data requirements, and success criteria for each performance objective are listed left to right in subsequent columns. The far right column includes the results achieved during the field demonstration. The following sections discuss each performance objective in greater detail.

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
1. Reduce primary energy for heating *(Energy)*	Natural gas (standard cubic feet [SCF]) or electricity (kilowatt hours [kWh])	Electric and gas use metered	Reduce primary energy use by 25%	19%
2. Reduce costs *(Finances)*	Heating energy costs ($)	Base rates for electricity and fuel	10% reduction in heating costs	(1%)
3. Reduce emissions *(Environment)*	Metric ton CO_2 equivalent	Conversions for fuels	Reduce CO_2 emissions by 15%	19%
4. Comfort	Maintain temperature within comfort range of building occupants	Indoor temperature readings and survey of occupants	Compliance with ASHRAE 55	Yes
Qualitative Performance Objectives				
5. Ease of installation	Ability of a technician-level individual to install the heat pump	Feedback from the technicians on installation time	A field technician team is able to install the system	Yes
6. Maintenance	Ability of a technician-level individual to maintain the heat pump	Feedback from the technicians on maintenance calls	A field technician team is able to operate the system	Yes

3.1 PRIMARY ENERGY AND COST

The energy performance objective compared the energy consumption of the CCHP to traditional natural gas furnace. The energy consumption of two similar zones was measured to achieve this comparison. Energy conversions were used to compare the performance of two heating technologies (natural gas furnace and electric heat pump) on a consistent basis. All forms of energy were converted to kWh. As reported in Table 1, the measured energy reduction was only 19%. Despite not achieving the overall performance objective, the energy reduction was still substantial. It is expected that future versions of this technology will achieve the 25% goal due to applying the recommended improvements. For example, the internally developed control program was not optimized to reach the best performance of the heat pump at each operating point during the field test. The next iteration of this technology would improve upon the results obtained.

The objective specifically referred to operating costs and it is separate from the maintenance and installation expenses. The purpose of the financial objective was to determine the financial savings from operating a CCHP compared to a furnace. The financial objective also helps

determine the payback if a CCHP is selected over a furnace. The operating costs for a CCHP and natural gas furnace (NGF) were computed from their energy consumption. The CCHP uses only electricity so its costs were calculated by multiplying the real energy consumption (kWh) by the electrical utility rate. The SCF consumed by the NGF was multiplied by the gas utility's rate and added to the cost of the electricity for operating its supply fan. This provided the total operating cost of a NGF.

The financial performance objective was not met. Table 1 shows that energy costs were 1% higher with the CCHP. There are two main reasons for this occurrence. First, the energy savings (from performance objective 1) were not as high as originally anticipated. Because the energy savings drive the cost savings, it is not surprising that the second performance objective was not met. Second, natural gas is currently an inexpensive fuel when compared to electricity. Even if a CCHP fails to achieve cost savings as compared to a NGF, there is still a substantial opportunity for cost savings from this technology. The operating cost of a NGF is difficult to beat right now since natural gas prices are at historic lows. The CCHP will fare better in comparison to other technologies, such as electric resistance heating. The CCHP is the best option in locations where electricity is the only option, such as when fossil fuel sources for heating are not readily available.

3.2 CO_2 EMISSIONS AND COMFORT

The environmental objective determined a reduction in the CO_2 emissions by deploying a CCHP. Installing an electric heat pump is environmentally beneficial compared to natural gas heating. Heat pumps can be powered by electricity through renewable methods and become emission free. A NGF can never be emission free because it cannot operate off renewable energy.

Data for the environmental performance objective is obtained from previously obtained data in the energy performance objective. Environmental performance data is obtained indirectly with a greenhouse gas equivalencies calculator. Using references from the U.S. Environmental Protection Agency (EPA), the energy consumed by each heating method was converted into kilograms (kg) of CO_2. The greenhouse gas equivalency calculation is an estimate but assisted in determining if the environmental objective was achieved. Once this conversion is computed the environmental objective was to be analyzed statistically. The results of the field demonstration show that this percentage was 19%, and therefore enabled the environmental performance objective to be met. If electric power is produced from "dirtier" fuels, then the CCHP must have even greater energy savings.

The purpose of the comfort performance objective was to determine whether a CCHP can provide a zone that is comfortable for human occupancy. The comfort performance metrics are guidelines found in ASHRAE Standard 55 – "Thermal Environmental Conditions for Human Occupancy." ASHRAE Standard 55 has been almost universally adopted by state and municipalities as the benchmark for quantifying occupant comfort. Data was collected using temperature and relative humidity sensors placed outdoors and in the two buildings. This allowed a direct comparison of how well a CCHP is able to maintain the temperature as compared to a NGF. This comparison made the reasonable assumption that the test and control zones within the same building are being used in a similar fashion. The variables collected during the demonstration were evaluated according to ASHRAE standard 55. In addition to zone

temperature and relative humidity, other variables involved with analysis, such as soldier clothing insulation and air speed, were estimated. On this basis it was found that the CCHP and the NGF were able to meet acceptable levels of comfort, 80% of CCHP average temperatures lie within and only 50% of high room temperatures are outside the comfort zone.

3.3 INSTALLATION AND MAINTENANCE

The installation performance objective evaluated an HVAC contractor’s ability to install the CCHP. The CCHP team chose a qualified, Trane and North American Technician Excellence (NATE) certified technician to perform the installation. The installation objective determined the ease of installation and corrected barriers to the install. The metric used in the installation objective was feedback obtained from the technician performing the installation. The technician was able to successfully install two CCHPs. Therefore, the installation performance objective was met. This finding was based on two prototype installations, so more data is needed to fully evaluate this objective.

The ability of an HVAC technician to maintain, repair, and operate the CCHPs was included in the maintenance performance objective. The contractor chosen for the installation also performed maintenance on the CCHP. The purpose of the maintenance objective was to determine the ability of a technician to maintain, repair, and operate a CCHP. The metric for the maintenance objective is feedback given by the technician. The technician was able to successfully maintain each CCHP. Therefore, the maintenance performance objective was met. More installations are needed to fully evaluate this objective. This finding was based on two prototype installations, so more data is needed to fully evaluate this objective.

4.0 SITE DESCRIPTION

The CCHP demonstration site was the Camp Atterbury Joint Maneuver Training Center (CAJMTC). It is an Army National Guard base located near Edinburgh, Indiana, a rural town about 1 hour south of Indianapolis. Constructed in 1941, the 33,000 acre military base has been used as a training center to support the Global War on Terror. Two barracks buildings were selected for testing two experimental CCHPs. Due to the large number of occupants in each building, ~80 soldiers, doors and windows would be left open, which provided a real world testing site for these new units.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The red star in Figure 2 shows the location of Camp Atterbury and the Purdue “Flying P” logo indicates the location of Purdue University’s flagship. The demonstration site is 100 miles (approximately 2 hours) from Purdue University.

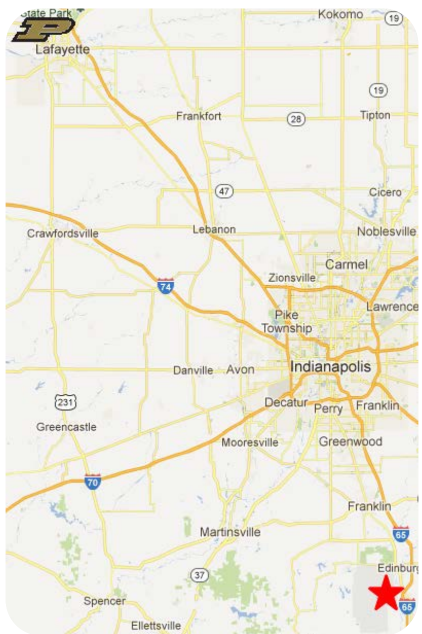

Figure 2. Map between West Lafayette and Camp Atterbury.

Camp Atterbury has a number of features that made it an ideal location for hosting the CCHP field demonstration:

- Camp Atterbury has many buildings of similar size and construction. These buildings are also similar to what is found on many other military bases.
- Temperatures at Camp Atterbury can be as low as -10°F and as high as 90°F. These varying weather conditions allowed the CCHP to operate through different stages of heating and cooling and provided insight to the robustness of the CCHP components.

- Camp Atterbury is a short 2 hour drive from the main campus of Purdue University in West Lafayette, Indiana. This was extremely helpful for installing, monitoring, and maintaining equipment used in the field demonstration.
- Camp Atterbury staff were responsive and helpful during visits from the CCHP team.

4.2 FACILITY/SITE CONDITIONS

Figure 3 is an example of the multi-purpose buildings that were chosen for the field demonstration. They are single story buildings constructed of cinderblocks and are approximately 6000 square feet (ft^2). The windows are single-paned with an aluminum frame. The buildings were constructed more than 50 years ago, but have been recently upgraded and now feature modern HVAC systems, tankless water heaters, and sheet metal roofs.

Figure 3. Barracks multi-purpose building at CAJMTC.

A blueprint of the buildings is shown in Figure 4. The original mechanical rooms consisted of two separate furnaces, each with a split direct expansion (DX) air conditioner. These are the conventional means of heating and cooling a building in northern climates. One conventional system supplies comfort to the northern occupied zone and the other to the southern occupied zone. The lavatory has a supply diffuser from each system so each conventional system provides comfort to the lavatory.

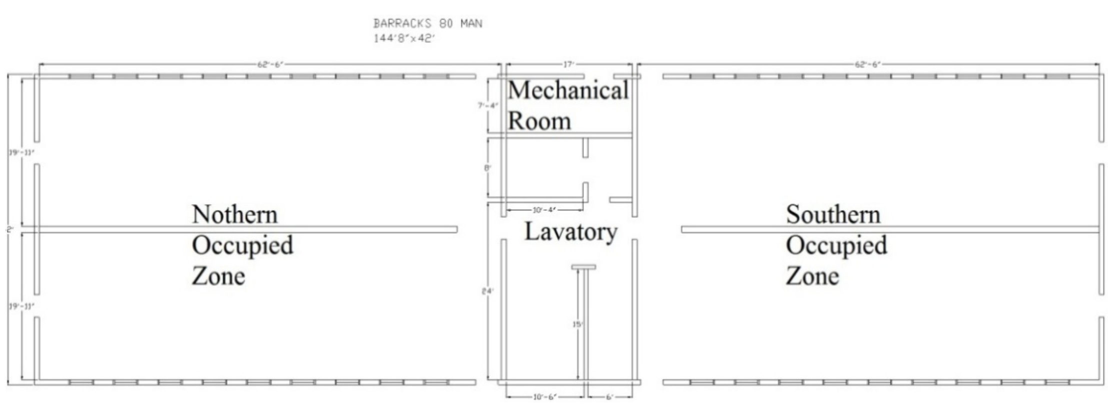

Figure 4. CAJMTC barrack blueprint.

One building with two zones provided a near ideal experiment for comparing two different HVAC systems. The experimental plan resulted in installing a CCHP in a building (Building 113) to provide comfort to the southern occupied zone and installing the second CCHP in another barracks (Building 114) to provide comfort to the northern occupied zone.

The annual weather conditions in Indianapolis, Indiana are summarized in Figure 5, which is a graphical representation of the TMY3 outdoor temperatures. The vertical axis is the outdoor temperature and the horizontal axis is the duration in hours. Figure 5 shows that CAJMTC can experience temperatures below 25°F (the threshold temperature for conventional heat pumps) for over 1100 hours in one year. Even though it is not as cold as some locations, Edinburgh, Indiana, (the location of CAJMTC) provided a sufficient amount of cold weather data to confirm the operation and advantages of a CCHP.

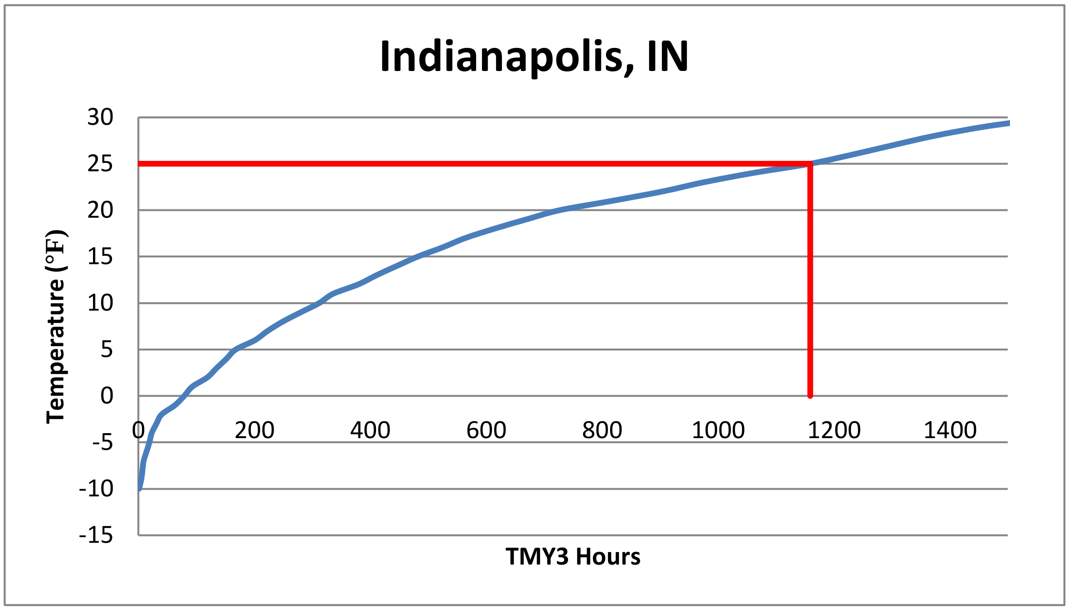

Figure 5. Temperature profile.

Observations during the field demonstration indicated the military does not operate with energy efficiency as a priority. Multiple times doors were left open (Figure 6) and windows were not locked shut. Additionally, lights were left on and the HVAC set points were at the occupied level while the building was vacant for extended periods of time.

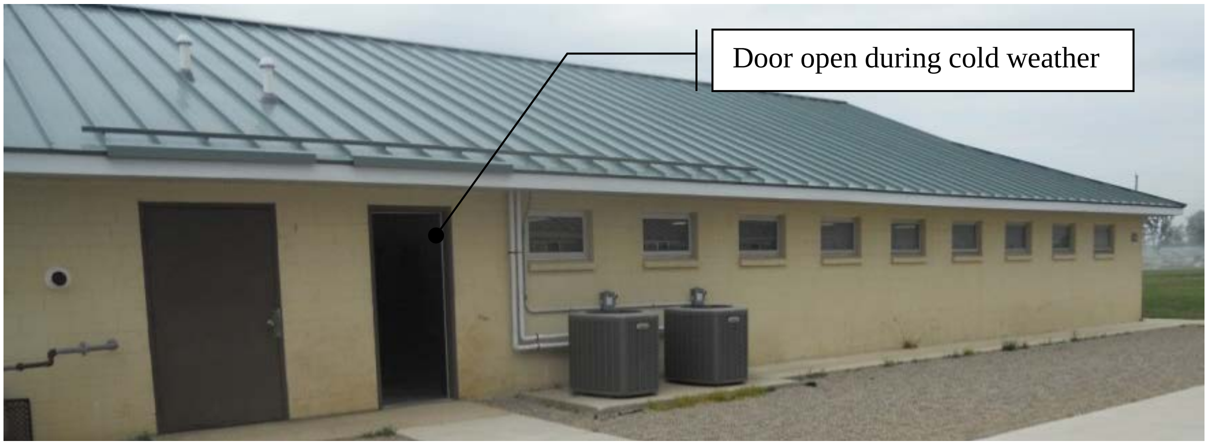

Figure 6. Building 114 operations.

5.0 TEST DESIGN

This field demonstration evaluated the potential for energy and cost savings from the deployment of a CCHP. The experimental design allowed for a direct comparison of the performance of a traditional gas-fired furnace to the performance of a CCHP. The methods and materials for this project are explained so that similar results can be achieved from repeated and independent experimentation.

5.1 CONCEPTUAL TEST DESIGN

The multi-purpose buildings that normally serve as barracks for soldiers were selected as the buildings for the CCHP demonstration at Camp Atterbury. The two buildings (Buildings 113 & 114) selected are oriented north to south and are within 100 feet of each other. Figure 7 shows that each building is split into two halves separated by a mechanical room and lavatory. The middle zones shown in green and blue are the mechanical rooms and lavatories, respectively.

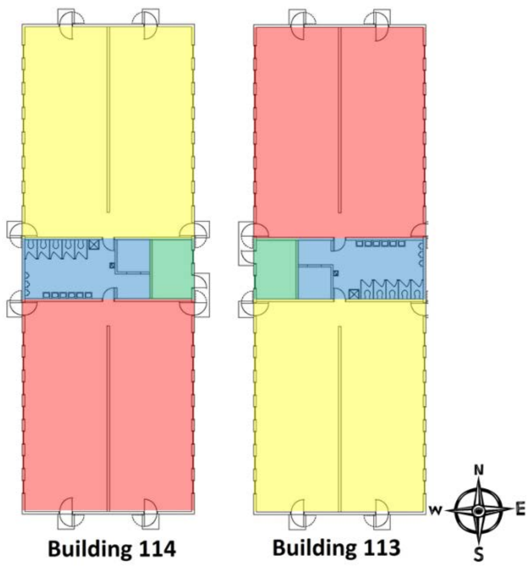

Figure 7. General experimentation plan.

The experiment was set up so that a direct comparison between the baseline and experimental HVAC systems could be made in one building. The red highlighted zones in Figure 7 used the baseline HVAC system, which was a split-system air conditioner with a NGF. The yellow zones were conditioned by the CCHP.

5.2 BASELINE CHARACTERIZATION

Direct measurements of outdoor temperature conditions were taken as the field demonstration was conducted. Both outdoor temperature and outdoor relative humidity were tracked. This outdoor data is the basis for comparisons to energy modeling based on TMY data. Outdoor temperature is the key independent variable that dictates overall performance of the CCHP system, which is why many of the findings are expressed with respect to outdoor temperature.

The experimental design was planned so that direct measurements of baseline and experimental data could be collected at the same time. As described in Section 4, each building (113 and 114) had two independent but nearly identical zones. One zone had a NGF that provided baseline (reference) values for energy, indoor temperature, and indoor relative humidity. The other zone in the building had the CCHP that provided experimental values for energy, temperature, and relative humidity. With this approach, a direct and valid comparison of baseline and experimental performance was made. Energy was the core value for the demonstration, because the energy data drives the two other quantitative performance objectives. The energy objective is a direct measurement. The financial objective is computed from a comparison of the energy costs for electricity and natural gas. The environmental objective is also computed by converting the energy for electricity and natural gas into CO_2 equivalent emissions.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The field demonstration directly compared the performance of a CCHP to a conventional HVAC system in two zones of one building. This same test was conducted in two separate buildings. The mechanical housing, Figure 8, is the installed unit. If a third party programmable controller was not required then the only difference between installing a CCHP compared to a traditional heat pump would be the wiring and an additional line set.

Installing the CCHP components into an existing building without interfering in its operation was desirable while monitoring the performance of the CCHP and traditional HVAC equipment. The mechanical room provided ample space for most of the components and monitoring equipment. Additionally, the large attic allowed more ductwork to be installed, which allowed for an easy transition between the CCHP and existing conventional system. Due to the experimental nature of the CCHP, it was advantageous to keep the existing HVAC system as a backup. Figure 9 shows that this was accomplished by adding new ductwork in parallel to the existing ductwork to allow either system to operate.

Figure 8. Mechanical housing installed at CAJMTC.

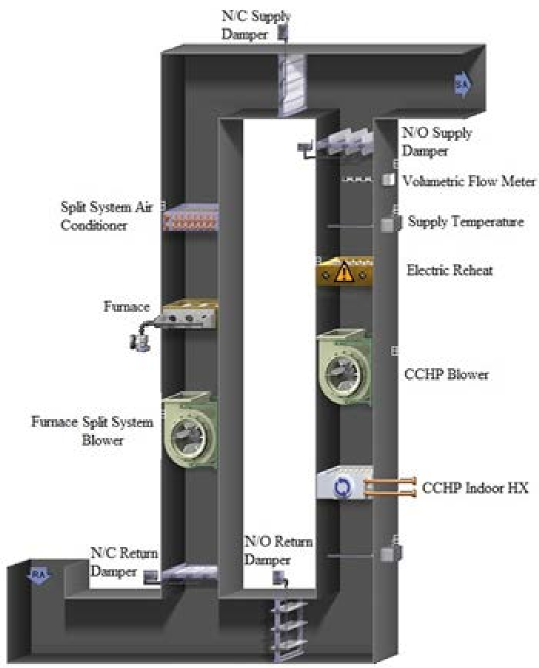

Figure 9. Building integration.

The right column of ductwork represents the CCHP component integration into the existing (left column) ductwork containing the split-system air conditioner and furnace. During normal CCHP operation, there were two open dampers and two closed dampers to force air flow through the right column so that comfort is provided by the CCHP system. In the event of CCHP system failure, the dampers reverse their operation so the dampers that were once open are now closed and vice versa. This now forces the air to flow through the conventional system (left column) so that building conditions are not interrupted due to any experimental failure.

The CCHP has seven different modes of operation, which includes single stage cooling, single stage heating, two-stage heating, defrost, oil equalization, oil return, and free cooling. A control program uses a variety of temperature and pressure inputs to determine which mode is active at any given time. Figure 10 is a flow chart that provides an overview of how these elements interact to form the control strategy for the CCHP.

The sequence begins in the upper left hand corner at the “START” ellipse. The diamonds represent a conditional statement where, if the statement is false the path flows to the right and if the statement is true the path moves downward. The rectangles are high level program elements that contain detailed conditions and other program elements within them. Upon reaching the “END” ellipse, the sequence of operation repeats itself as illustrated with the circular arrow at the bottom-center. A nomenclature list is provided in Figure 10 to describe the abbreviations.

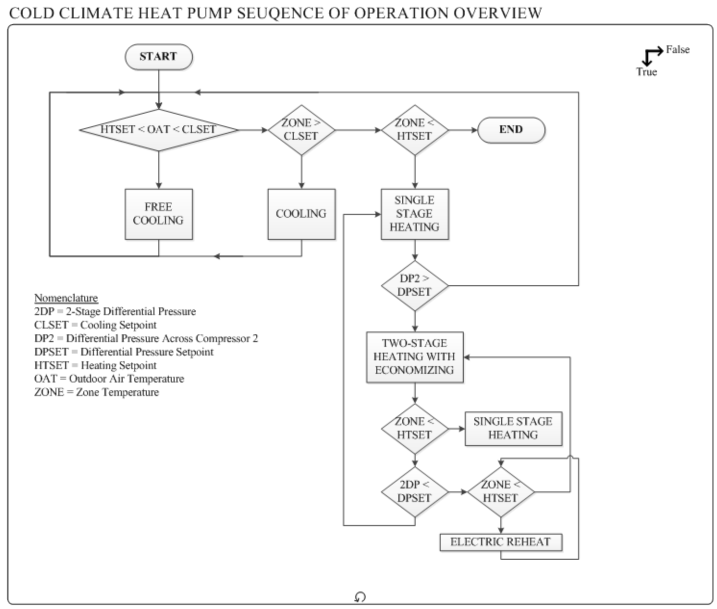

Figure 10. Control strategy overview.

5.4 OPERATIONAL TESTING

Table 2 summarizes the 2 year project to demonstrate a CCHP using the tasks that were established for the management of this project. Design work began in March of 2011 and continued for 6 months. The CCHP system was fabricated and tested in psychrometric chambers at Purdue University's Ray W. Herrick Laboratories over a 7 month period, ending in December of 2011. The field demonstration at Camp Atterbury in Edinburgh, Indiana is Task E (Monitoring & Refine) and lasted from January 2012 through April 2013. Since that time, the emphasis has shifted towards commercializing the technology.

Table 2. Gantt chart of CCHP field demonstration.

Tasks	2011										2012												2013							
	Month																													
	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
a. Design	■	■	■	■	■	■																								
b. Fabrication				■	■	■	■	■	■	■																				
c. Experimental Plan					■	■	■	■	■																					
d. Installation								■	■	■	■	■																		
e. Monitor & Refine											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
f. Commercialization																				■	■	■	■	■	■	■	■	■	■	■
g. Reporting	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

As shown in Table 2, the field demonstration at Camp Atterbury commenced in January 2012 and ended 16 months later in April 2013. This work proceeded in three phases: 1) system start-up, 2) cold climate testing, and 3) shutdown and demobilization. Each phase is discussed in more detail in the paragraphs that follow.

System start-up was for 9 months, from January 2012 through September 2012. Much of this work involved testing and improving the CCHP control algorithm to achieve stable long term operation.

Cold climate testing commenced in October 2012, as soon as the outdoor temperature was cold enough that heating was needed. This work continued for the entire 6 month heating season, which lasted through March 2013. The goal during this time was to run the CCHP systems every day, all day as the primary source of heat for the buildings used in the field demonstration.

Shut down and demobilization took place from May 2013 and proceeded through the end of the contract. The CCHP test equipment is still installed at Camp Atterbury to support further commercialization work that is still underway.

5.5 SAMPLING PROTOCOL

Instrumentation was selected based on accuracy, resolution, and compatibility with the data acquisition system. A summary of the instrumentation used for evaluating the performance objectives is illustrated in Table 3.

Table 3. Performance objective sampling.

Instrument	Measurement	Units	Accuracy	Frequency
CCHP Electric Meter	Energy	kWh	±0.5%	0.5 COV
Furnace Electric Meter	Energy	kWh	±0.5%	0.5 COV
Gas Meter	Energy	SCF	±0.5%	1 COV
Outdoor Conditions Sensor	Temperature	°F	±0.36°F	10 min
	Relative Humidity	%	±2.0%	10 min
Indoor Comfort Sensors	Temperature	°F	±0.36°F	10 min
	Relative Humidity	%	±2.0%	10 min

The gas and electric meter data is collected on a change of value (COV) basis. This is beneficial because during low heating loads the server will not be overloaded with insignificant data compared to sampling at set intervals. However, when there is a high heating load, more data points are collected because the systems are consuming more energy.

5.6 SAMPLING RESULTS

A significant amount of instrumentation was installed on the CCHP to record temperatures, pressures, and its overall electric consumption. Additional instrumentation provided verification on the status of individual components as well. Because a majority of these measurements were not used to generate the results needed for the performance objectives, only points of significance are used in this section. Also, due to the large amount of data collected from all 11 data sets, only one data set is selected and presented in this section. Therefore, only points of significance from the selected data set are shown within this section. A summary of all 11 data sets collected can be seen in Table 4.

Table 4. Summary of CCHP test interval.

Building	Data Set No.	Data Collection Period			Hours:Minutes of Data	Low Outdoor Temperature [F/C]	Average Outdoor Temperature [F/C]	High Outdoor Temperature [F/C]
114	1	10/12/2012 9:40 PM	-	10/13/2012 1:10 PM	15:30	42/5.6	53/11.7	68/20
	2	10/15/2012 2:40 PM	-	10/16/2012 1:05 PM	22:25	39/3.9	52/11.1	65/18.3
	3	10/25/2012 8:22 AM	-	10/26/2012 3:29 PM	31:07	46/7.8	65/18.3	82/27.8
	4	10/27/2012 1:50 AM	-	10/27/2012 3:45 PM	13:55	38/3.3	45/7.2	55/12.8
	5	1/4/2013 11:00 AM	-	1/5/2013 9:05 AM	22:05	17/-8.3	27/-2.8	37/2.8
	6	1/10/2013 9:35 AM	-	1/17/2013 1:55 AM	160:20	19/-7.2	41/5	67/19.4
	7	1/25/2013 1:25 AM	-	1/25/2013 6:10 PM	16:45	21/-6.1	25/-3.9	30/-1.1
	8	2/14/2013 10:30 AM	-	2/15/2013 7:25 PM	32:55	30/-1.1	39/3.9	53/11.7
113	9	2/1/2013 2:45 PM	-	2/4/2013 4:45 AM	62:00	17/-8.3	27/-2.8	42/5.6
	10	2/13/2013 3:00 PM	-	2/14/2013 12:50 AM	9:50	40/4.4	44/6.7	49/9.4
	11	2/14/2013 9:40 AM	-	2/15/2013 9:10 PM	35:30	29/-2.2	40/4.4	59/15

The data set that was selected for discussion in this report included both two-stage and single-stage operation and also had a relatively small time span for ease of plotting. The seventh data set, January 25th, for building 114 was found to meet these criteria. The measurement points of significance were any values that were needed to evaluate the performance objectives as well as additional points that provide significant insight into the operation of the CCHP.

To monitor the air side performance of the heat pump, air temperature sensors were located before and after the indoor heat exchanger. Also, the temperature sensors located within the conditioned zones of the building were used to evaluate the effects of the CCHP and furnace operation on the space. Figure 11 provides a summary of all the zone temperatures, CCHP supply and return temperatures, and the CCHP control temperature. Also, as a reminder, please note that for data set seven, the heat pump provides heating to the northern half of building 114 and the furnace supplies the southern half.

The first point to note from Figure 11 is the high temperatures of the supply air relative to the other readings. These high supply temperatures are dependent on the number of stages the CCHP is utilizing. When in two-stage mode, higher supply temperatures are observed because the CCHP is running at higher pressures. The larger amount of heat available when using two-stage compression becomes evident with this comparison to single-stage operation.

The northern zone has different temperature trends than the southern zone due to the difference in the operation of the CCHP from a natural gas furnace. In Figure 11, the southern zone temperatures show averages around 85°F while the northern zone has lower averages closer to 70°F. The northern zone has a larger temperature difference between measurement points than between points for the southern zone. It is believed that the larger temperature differences between points for the CCHP are due to the ductwork modifications made to allow for integration into the existing duct work.

The comparison between the CCHP and furnace energy consumption is plotted and shown as Figure 12. The energy consumption for the furnace is shown as a rate, SCF of natural gas per hour. Note that data set seven does not have a complete record of the energy rate but the totalized amount of natural gas is available to make primary energy comparisons. The furnace shows some electricity consumption due to use of the blower. The CCHP operates using only electricity as shown in the figure. The power consumption of the CCHP increases by more than double for this data set when switching from single-stage to two-stage mode. Between the hours of 2:00 to 10:00 a.m., the CCHP uses roughly 13kW of electricity, but during single-stage mode, between the hours for 4:00 to 6:00 p.m., the CCHP uses only 6kW of electricity. The doubling of the CCHP electricity consumption is still able to provide efficient heating due to a corresponding multiplier increase of the CCHP heating capacity.

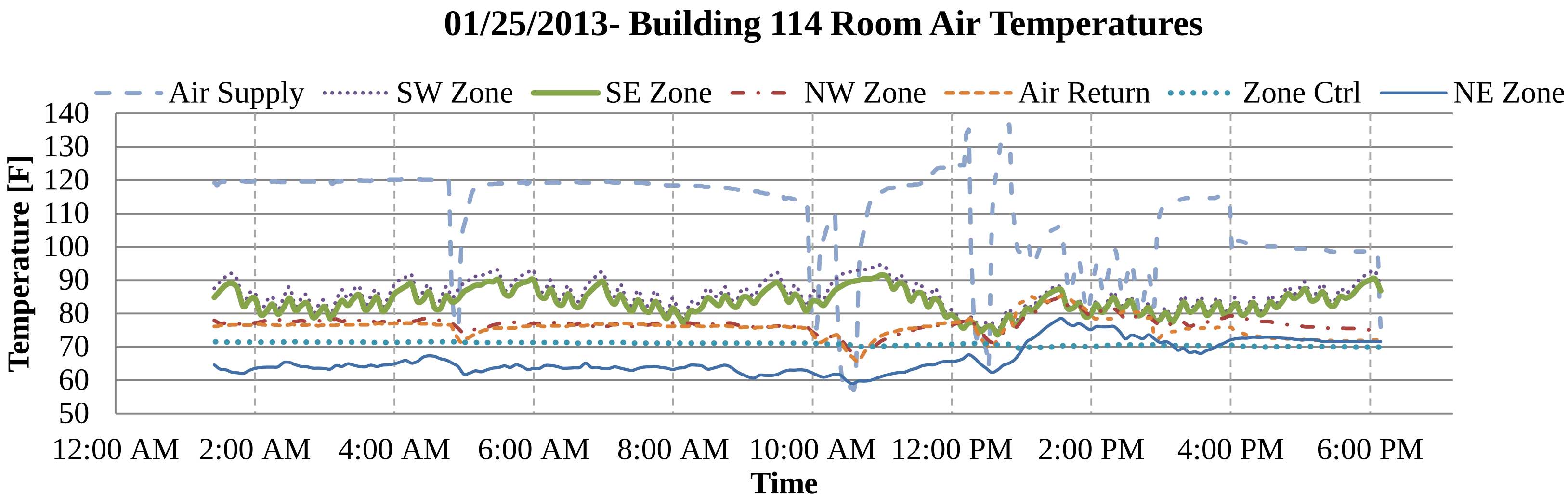

Figure 11. Data set 7 – room air temperatures.

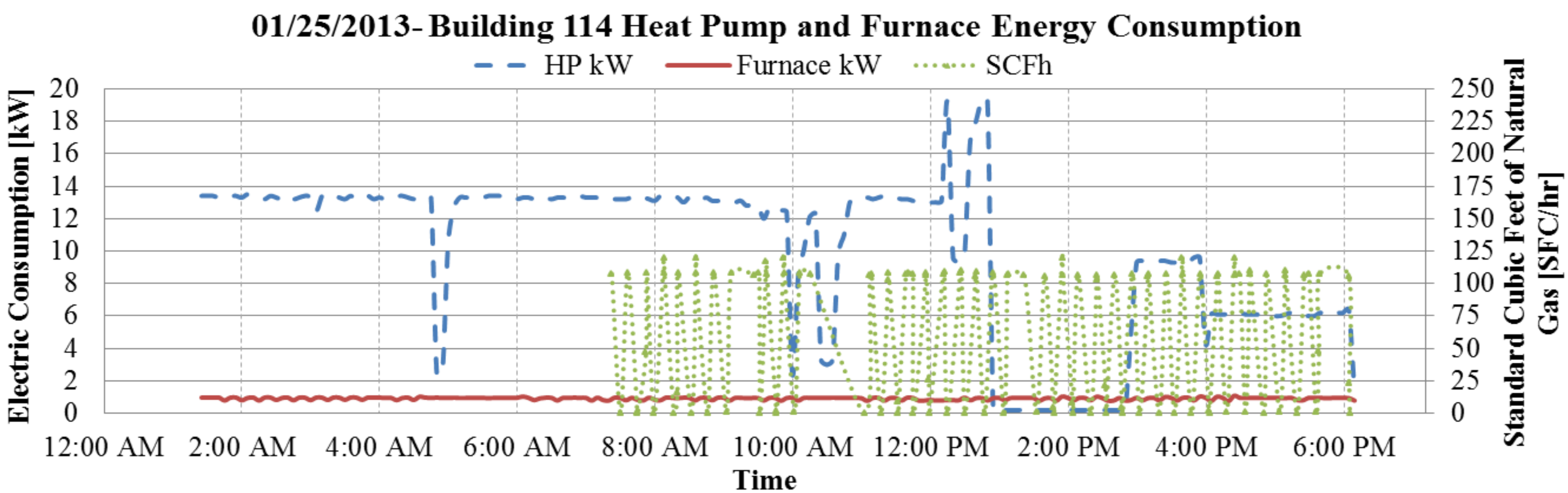

Figure 12. Data set 7 – energy consumption of heat pump and furnace

6.0 PERFORMANCE ASSESSMENT

A laboratory environment (e.g., psychrometric room testing) is useful for testing components of an HVAC system and establishing equipment performance for rating purposes. However, a field test is the ultimate step for evaluating a new technology prior to full commercialization. Variables that cannot be controlled by the experimenters are certainly introduced which creates an imperfect, but real world environment. During the CCHP test, there were instances where doors and windows were left open, which were costly in terms of achieving optimal energy performance but are also part of a real world operation.

The energy consumption was monitored over time to provide a direct comparison of primary energy. Cost and emissions are computed directly from this energy consumption data. Table 5 and Table 6 summarize the results achieved for performance objectives 1, 2, and 3. Table 5 is the energy, cost, and emission data for building 114 (CCHP and furnace supplying comfort to the northern and southern zones of building 114, respectively) and Table 6 has the same information for building 113 (CCHP and furnace supplying comfort to the southern and northern zones, respectively). The results are presented as a direct comparison between the CCHP and NGF on a source (primary) energy basis in kWh.

6.1 PRIMARY ENERGY AND COST

Tables 5 and Table 6 illustrate the importance of comparing each method on a primary energy basis. The CCHP uses only electricity, while the NGF uses electricity for the fan and burns natural gas to generate the heat. Taking both the electricity and the natural gas back to primary energy requires making energy conversions but allows for both systems to be accurately compared. The assumptions necessary for these conversions are listed in Table 6-3 of the final report.

Outdoor conditions for all data sets can be referenced by looking at Table 4. If the three data sets with higher consumption for building 114 were able to show equivalent primary energy consumption as the furnace, then the primary energy savings for all data sets would be at approximately 26% instead of the 19% recorded. The system controls play an important part in primary energy consumption of the CCHP. Controls for a furnace are more straightforward because cycling for a furnace does not create a large amount of inefficiencies.

The financial performance objective was evaluated by taking the energy consumption of each system, the CCHP and NGF, and using utility rates to calculate the individual operating costs. The CCHP system required only the electricity rate while the NGF needed both a natural gas rate and an electricity rate. Two sets of utility rates, CAJMTC and residential, were used to generate two sets of cost comparisons that can be seen in Table 6-3 of the final report. The rates for Camp Atterbury were obtained from CAJMTC staff and the residential rates were referenced from the 2011 Energy Information Administration (EIA) data book for Indiana. Two different sets of rates were used to provide a comparison between the energy costs for a military base and for a typical residence.

Table 5. Building 114 results for energy, cost, and emissions.

	Data Set No.	1	2	3	4	5	6	7	8
CCHP (Building 114)	Electric Meter Real Energy (kWh)	56.0	60.0	67.9	57.6	161.1	1209.6	99.9	174.7
	Primary Energy (kWh)	143.3	153.5	173.7	147.3	412.0	3093.9	255.4	446.9
	DoD Operational Cost ($)	$4.48	$4.80	$5.43	$4.61	$12.89	$96.76	$7.99	$13.98
	Residential Operational Cost ($)	$5.88	$6.30	$7.13	$6.05	$16.91	$127.00	$10.49	$18.34
	CO_2 Emissions (kg)	26.3	28.2	31.9	27.0	75.6	567.8	46.9	82.0
Furnace (Building 114)	Electric Meter Real Energy (kWh)	12.9	18.1	26.6	12.0	20.3	141.0	15.4	23.9
	SCF of Nat. Gas	266.5	298.5	489.5	1010.0	1762.1	7386.3	1188.9	1960.8
	Primary Energy (kWh)	112.1	134.9	213.2	330.2	574.4	2551.5	392.0	642.6
	DoD Operational Cost ($)	$2.29	$2.85	$4.43	$5.71	$9.90	$46.00	$6.82	$11.13
	Residential Operational Cost ($)	$3.88	$4.73	$7.42	$10.81	$18.80	$84.68	$12.86	$21.06
	CO_2 Emissions (kg)	20.6	24.8	39.1	60.6	105.4	468.3	71.9	117.9

Table 6. Building 113 results for energy, cost, and emissions.

	Data Set No.	9	10	11
CCHP (Building 113)	Electric Meter Real Energy (kWh)	454.7	134.2	43.6
	Primary Energy (kWh)	1163.2	343.1	111.4
	DoD Operational Cost ($)	$36.38	$10.73	$3.48
	Residential Operational Cost ($)	$47.75	$14.09	$4.57
	CO_2 Emissions (kg)	213.5	63.0	20.4
Furnace (Building 113)	Electric Meter Real Energy (kWh)	52.2	26.7	6.0
	SCF of Nat. Gas	6579.7	2258.4	579.8
	Primary Energy (kWh)	2085.0	738.0	187.3
	DoD Operational Cost ($)	$35.10	$12.75	$3.20
	Residential Operational Cost ($)	$67.73	$24.16	$6.11
	CO_2 Emissions (kg)	382.7	135.4	34.4

The operating cost for the CCHP was approximately the same as one of the NGF, 1% more, when using the residential utility rates. This is in spite of the CCHP consuming less primary energy, but is due to the low cost of natural gas. Residential customers currently are paying record low prices for natural gas. The operating cost for the CCHP at CAJMTC was about 44% more than the NGF. Commercial users like CAJMTC are paying even less for utilities because long term purchase agreements that are negotiated before the natural gas is used. Ultimately, the CCHP technology will be most competitive in locations where fossil fuel sources are not available. Although a heat pump will have significant energy savings as compared to an electric furnace.

6.2 CO_2 EMISSIONS AND COMFORT

Previous studies have shown that heat pumps are only environmentally friendly from a CO_2 perspective when the electricity is produced by renewable means. However, for the field demonstration, the electricity used is assumed to be produced by a natural gas power plant. If the CCHP were to consume less primary energy than a NGF then, a CCHP would actually be better for the environment on a CO_2 basis. By using the primary energy consumption, both percent savings for primary energy and emissions are the same at 19%. For different locations, the electrical grid may be powered by a larger percentage of renewable power that lends to a smaller amount of CO_2 production per kWh of electricity.

To evaluate the comfort performance objective, ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, was applied to quantitatively evaluate the room conditions. Compliance with the standard is estimated to predict at least 80% of the occupants are comfortable. The standard was satisfied for the majority of the maximum and average supply temperatures for the heat pump. Almost all of the minimum supply temperatures of the heat pump were outside the standard. It should also be noted that the furnace operation requires a higher air velocity to ensure adherence with the standard. All of the maximum supply temperatures and roughly half of the average supply temperatures for the furnace lie outside of the low air speed zone and about half of the low supply temperatures for the furnace were outside the low air speed zone completely. The lower supply temperatures of heat pumps are known and can cause user discomfort if the air distribution system is designed improperly. From the results, it can be concluded that the heat pump will satisfy 80% of the occupants a majority of the time.

6.3 INSTALLATION AND MAINTENANCE

The installation of the CCHP was performed by a HVAC contractor, who was familiar with installing heat pumps. The main difference for an installation between a CCHP and a traditional air-source heat pump was an additional component. Both systems utilize an indoor and outdoor unit but the CCHP had a compressor housing unit that contained all the compressors and auxiliary equipment needed. The indoor and outdoor units for the CCHP were off the shelf components that are currently used in a pre-packed air-source heat pump. More space is needed for the CCHP than traditionally available in outdoor units. Ideally, the outdoor unit would be slightly redesigned creating enough space to contain all the essential equipment needed for the CCHP. With this small change, the installation of the CCHP becomes almost identical to a traditional air-source heat pump.

Most maintenance of air-source heat pumps involves charging refrigerant, replacing fan motors or blades, replacing a compressor or replacing a bad sensor. All of these tasks could be completed on the CCHP by a HVAC technician with minimal difficulty. The redesign of the outdoor coil would need to take into account allowing the ability for the HVAC technician to conduct any maintenance on the CCHP. Tasks that would be considered additional maintenance compared to a traditional heat pump were not identified during the field demonstration. More installations would be needed to determine if different maintenance tasks are required by the CCHP.

6.4 SEASONAL PERFORMANCE RATINGS

For air-source heat pumps, there are three different ratings for measuring its seasonal performance: 1) the seasonal energy efficiency ratio (SEER) determines the cooling performance over the cooling season, 2) the heating seasonal performance factor (HSPF) determines the heating performance over the heating season, and 3) the seasonal COP provides the heating or cooling performance for either the entire heating or cooling season. The difference between the SEER or HSPF and the seasonal COP is that the units are used for energy and electricity. The seasonal COP uses the same units for both energy and electricity while SEER or HSPF use British Thermal Units (BTU) for energy and kWh for electricity. A SEER rating cannot be calculated for the CCHP because the field demonstration was conducted during the heating season.

Data was to be collected over an entire heating season and used to calculate a value similar to the HSPF. This is done by summing all the energy delivered to the building, in BTUs, during the heating season and dividing this sum by the total amount of electricity consumed, kWh, during the same period. These units are the same used for the HSPF to have a rough baseline comparison. The value calculated using experimental data cannot be labeled as a HSPF in order to avoid confusion with HSPF ratings of off-the-shelf equipment. Due to the complications encountered during the project, an entire heating season worth of data could not collected. In spite of this limitation, the data collected can be used to update the inputs of a building modeling program, Transient Systems Simulation Program (TRNSYS), to generate an experimentally adjusted, simulation heating seasonal performance.

6.4.1 Simulation Results

The TRNSYS model is run during only the heating season, from September to April, to predict the monthly and overall heating season performance of the CCHP. The overall heating seasonal COP from these results was calculated to be 3.75, which corresponds to a heating seasonal performance of 12.8 BTU/W-hr. A conference paper was published that presents the use of the TRNSYS model to predict the operation of the CCHP during the field demonstration (Caskey et al., 2012a).

6.4.2 Experimental Improvement

With a complete building model, improvements on the simulation results could be made by modifying references used by the simulation to better match the experimental data. The monthly electricity consumption and the monthly seasonal heating COP are plotted only for the months

during the heating season as shown in Figure 13. The new simulation predicts a seasonal heating COP of 2.25 or a heating seasonal performance of 7.7 BTU/W-h. The HSPF requirement for the DOE's appliance Energy Star rating is a level of 8.2 or above. To accurately compare the CCHP to existing HSPF ratings, the system would need to be tested in a laboratory to find its HSPF rating or a conventional heat pump would be tested over an entire heating season at the testing site to provide a measured heating seasonal performance.

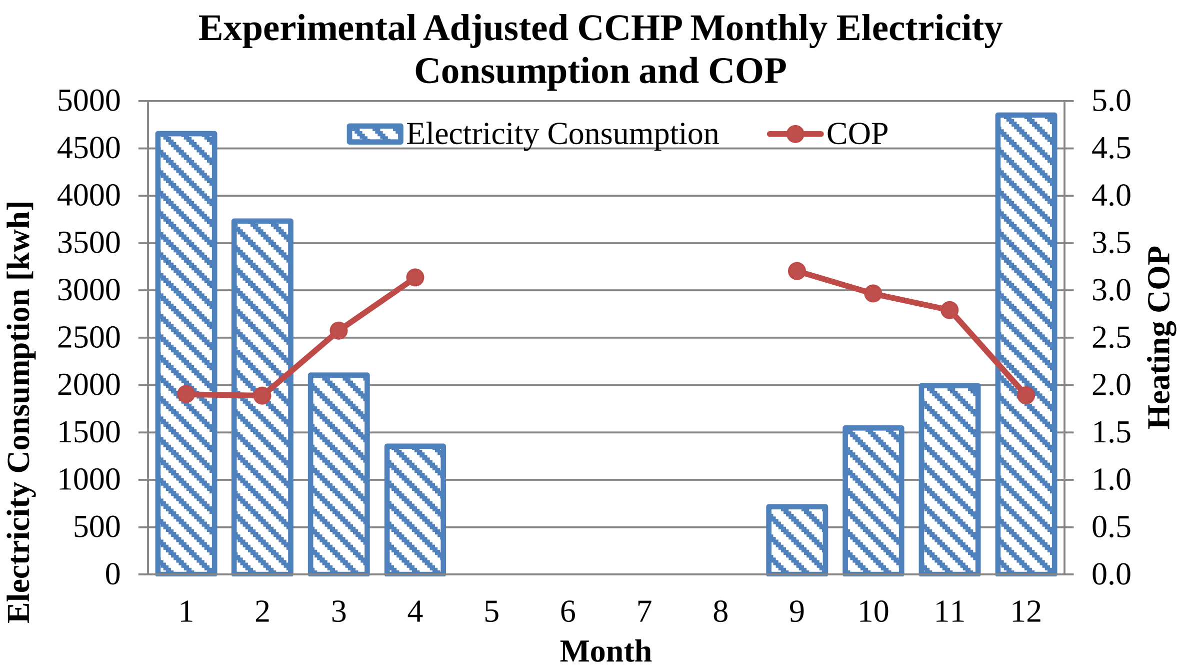

Figure 13. Experimentally adjusted TRNSYS model – monthly CCHP electric consumption and heating COP.

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7.0 COST ASSESSMENT

While operating costs are important, that information by itself fails to give a complete picture of the savings potential because other factors must be considered. A fully developed cost model must also include the first cost of the technology, installation costs, ongoing maintenance, and other factors. One challenge that the university/industry team faces right now is that information for the life cycle cost assessment is incomplete. What has been built and tested so far is a functional prototype of a CCHP. The equipment is heavily instrumented and is not optimized in terms of the components or functional layout. The cost information will change considerably as the device is value engineered to minimize parts, minimize assembly time, and create a strategy for long term maintenance.

Pre-commercialization work with the CCHP is going on now as part of a new partnership with Unico, Inc. of St. Louis, Missouri. Unico was recently awarded a 2 year contract from the DOE for the commercialization of a CCHP. Unico has licensed the two CCHP patents owned by Purdue University and has signed a research agreement with Purdue's Herrick Labs to support ongoing work towards full commercialization. Unico is a small, privately-owned business that makes a variety of unique HVAC products, including innovative small duct, high velocity air handlers and ducts along with chillers and heat pumps. Unico has metal manufacturing equipment and the ability to turn raw sheets of galvanized and stainless steel into our blower and coil cabinets.

7.1 COST MODEL

The market for CCHP includes both residential and light commercial customers. The market includes both new construction and retrofitting existing buildings. The market focus for the Unico CCHP would primarily be in the U.S. northern climatic zones five, six, seven, and eight, but the CCHP has the potential to be sold as a heat pump anywhere throughout the U.S. and Canada. Table 7 has the 2011 Air Conditioning, Heating and Refrigeration Institute (AHRI) data showing the number of outdoor condensing units shipped and sold. Based on this data, Unico will produce sizes 3, 4, and 5 ton CCHP with capacities ranging from 36,000 BTU to 65,000 BTU.

Table 7. Condenser sales for 2011.

Condensing Units Sold	3 ton	4 ton	5 ton
	1,175,000	637,000	572,000

AHRI data shows that there has been a continual increase in the number of heat pumps sold each year. Unico predicts that this trend will continue into the future as homeowners adopt the use of heat pump technology as the main source of heating and cooling for their homes. Unico also believes that as the 30% tax rebate for ground source heat pumps expires in 2016, the sales of air source heat pumps will increase even higher due to the higher cost associated with ground source heat pumps and the discontinuation of the rebates.

7.2 COST DRIVERS

A key to success of Unico's CCHP product is to develop a relationship with the National Rural Electric Cooperative Association (NRECA)-Cooperative Research Network (CRN), and other electric utility companies across the country, in an effort to partner with them on testing equipment at different locations throughout the U.S. and Canada. It will also be important to work with these particular organizations in an effort to secure rebates and incentives to offset the cost of Unico's CCHP. These rebates will allow a homeowner to realize a quicker return-on-investment (ROI) and shorter cost/payback on the CCHP product.

The total estimated U.S. market for residential and light commercial units between 3 and 5 tons is approximately $212 billion and 2,384,000 units per year. Once the CCHP product is ready for full commercialization, Unico will utilize its existing distribution channels of 219 HVAC wholesale partners with over 900 locations in the U.S. and Canada, as well as Unico's HVAC manufacturers' representatives (28 manufacturers' representatives covering the entire U.S. market and parts of Canada) to sell and stock the product into the market space. In order for air-source heat pumps to become serious contenders for use in colder climates, significant changes must be made for them to realize their true potential. Theoretical equations of efficiency, such as Carnot and Lorenz, show very high COPs. However, a practical system must include the temperature difference between the refrigerant and air, fan penalty, and compressor efficiency. These are compared in the Figure 14 and show that the proposed level (blue solid line) of COP is within reach from a practical point of view.

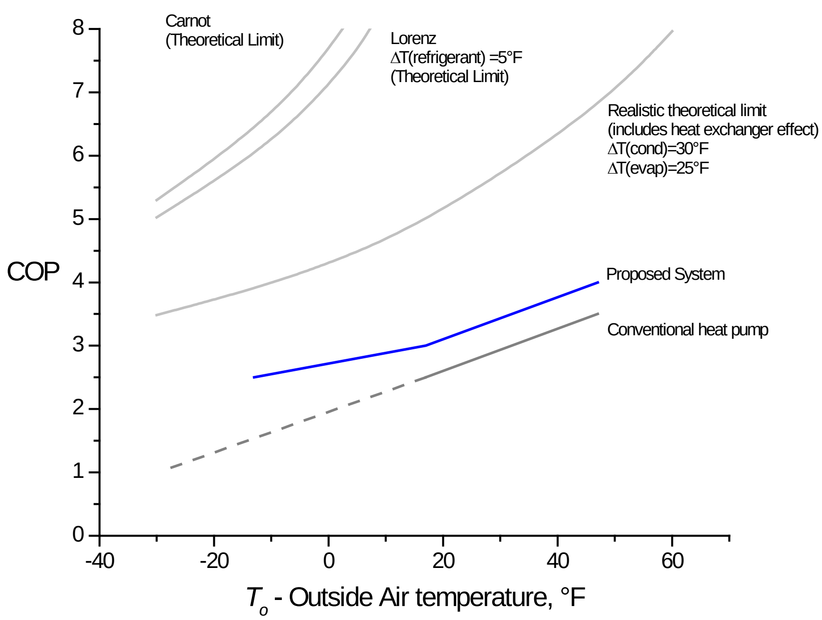

Figure 14. Unico projections for performance of commercialized CCHP system.

In real systems, the time averaged COP (seasonal) is less than steady state because of cycling and defrost degradation. As shown in Figure 14, Unico's projections for a seasonal COP of approximately 3.0 is higher than the COP of 2.5 that was achieved in this field demonstration. However, we believe that Unico's COP projections are achievable once improvements are made

to the components and controls of the prototype CCHP systems that were tested at Camp Atterbury. For purposes of comparison, the COP for a conventional heat pump averages 1.0 below freezing.

7.3 COST ANALYSIS AND COMPARISON

Table 8 shows the different types of energy costs listed by NRECA "Heating Fuel Cost Per Million Btu." Electricity is compared against natural gas, propane, and fuel oil. The cost projections for the Unico CCHP are included in Table 8 at two levels of performance, low and high, which illustrate the COP ranges summarized in Figure 14.

With the two exceptions of geothermal heat pumps and extremely low priced natural gas, the Unico residential CCHP solution will outperform every other energy category. To further enhance the cost/payback model, Unico plans to work with the NRECA and other national utilities to secure rebates and cash incentives for the homeowner to purchase and install a Unico CCHP. Estimated balance of materials cost show that Unico will have the ability to sell a 3 ton CCHP at a market competitive price that will yield a short pay back estimated at less than 5 years. With an average fuel oil heating bill of $1200 for a 2500 ft^2 building in a severe winter climate zone, compared to the Unico CCHP (High) of $562, the annual average savings from the Unico CCHP (High) would be $638/year.

Table 8. Heat cost comparison.

Heating fuel cost per million BTU								
Fuel	**Cost ($)**	**Unit**	**Energy Content**	**Units**	**Fuel Cost/ Million Btu ($)**	**Heating System**	**Heating System Efficiency (%)**	**Heating Cost/ Million Btu Delivered ($)**
Electricity	0.07	kWh	3413	Btu/kWh	20.51	Ducted Resistance	100	20.51
						Heat Pump (normal)	178	11.52
						Unico CCHP (Low)	262	7.83
						Unico CCHP (High)	315	6.51
						Heat Pump (Geo)	320	6.41
	0.10	kWh	3413	Btu/kWh	29.30	Ducted Resistance	100	29.30
						Heat Pump (normal)	178	16.46
						Unico CCHP (Low)	262	11.18
						Unico CCHP (High)	315	9.30
						Heat Pump (Geo)	320	9.16
	0.16	kWh	3413	Btu/kWh	46.88	Ducted Resistance	100	46.88
						Heat Pump (normal)	178	26.34
						Unico CCHP (Low)	262	17.89
						Unico CCHP (High)	315	14.88
						Heat Pump (Geo)	320	14.65
Natural Gas	1.00	therm	100,000	Btu/therm	10.00	Force Air, Typical	70	14.29
						Force Air, Condensing	90	11.11
	1.50				15.00	Force Air, Typical	70	21.43
						Force Air, Condensing	90	16.67
Propane	5.30 (about 1.85/gal)	ccf	252,400	Btu/ccf	20.99	Force Air, Typical	70	29.99
						Force Air, Condensing	90	23.32
Fuel Oil	2.60	gal	130,000	Btu/gal	20.00	Force Air, Typical	70	28.57

ccf = 100 cubic feet

8.0 IMPLEMENTATION ISSUES

Current CCHP technology continues to transition from a successful laboratory experiment to a commercially viable product. This chapter describes the most significant issues that were encountered during the field demonstration but were not fully resolved. These key issues include returning oil to the compressor, liquid flooding, subcooling, and most importantly, system control.

8.1 RETURNING OIL

Modern scroll compressors discharge a very small percentage of their oil at the refrigerant outlet. However, if the discharged oil is not returned to the compressor it will eventually result in the compressor seizing due to a lack of lubrication. To combat this, an oil separator was installed at the discharge of each compressor. When enough oil accumulates in the oil separator a float valve allows oil to flow through a filter and then back to the suction of the compressor.

The variable speed compressor had issues when operating at 1800 to 3600 revolutions per minute (RPM), speeds too low to capture oil from the oil line. Operating at these low speeds for a long duration will eventually lead to the same result as if an oil separator were not present (i.e., the compressor will be starved of oil and seize). The solution to the oil return problem required control logic and physical modification. Both solutions proved effective and were quite simple.

8.2 LIQUID FLOODING

Refrigerant migration occurs when liquid refrigerant travels to the lowest temperature part of the system while it is not operating. Refrigerant migration can cause slugs of liquid to enter the compressor upon start-up and damage it.

The refrigerant migration obstacle was overcome with a physical and programming change. The physical change required installing crankcase heaters, which are commonly found on commercially available heat pumps, and the programming change was a “pump down” strategy. A “pump down” operation involves closing the primary expansion valve while letting the compressor operate for a short time during CCHP shut down.

A solution that has not yet been implemented is to have only one oil separator and connect it to the discharge of compressor 2. Then the oil line would return to the inlet of the suction line accumulator. The accumulator would need to be pre-charged with oil to a level above the oil orifice. This would ensure any oil discharged by compressor 2 is returned to the accumulator to be sent to the suction of either compressor 2 or 1. Research performed by K.W. Yun in 1998 presented that the prior solution did extend compressor life. Returning oil to a pre-charged accumulator ensures that if any liquid refrigerant does enter the suction line of the compressor that it would be saturated with oil. Please note that during two-stage operation there must be an oil equalization procedure to balance out the oil levels between the two compressors if this solution were to be implemented.

8.3 SUBCOOLING

The absence of subcooling was primarily caused by a receiver that was installed. A refrigerant receiver helps to manage the amount of working charge in a vapor compression cycle. Liquid refrigerant is stored inside a fixed capacity chamber that acts as an inventory management device. The receiver can at best send saturated liquid unless it is flooded. So, an attempt to remove the receiver was tested. The removal of the receiver resulted in very high condensing pressures in two-stage operation. The pressures reached critical points in a matter of minutes. Pre-set pressure safeties in the programming logic prevented any serious damage. Therefore, a receiver or some other method of managing refrigerant inventory is mandatory.

8.4 SYSTEM CONTROLS

Due to the novel technology employed by the CCHP, most of the system controls had to be developed in house. Once the CCHP was installed, these controls had to be modified using several iterations to improve the system operation and response to the building conditions. The CCHP had to be brought off-line before a new control program could be uploaded. If a mistake with the logic existed or the new program did not perform as desired, the CCHP would be taken off-line again. For example, the compressor speed control during two-stage operation would cause a fault and shut down the CCHP. Because the system was already installed, testing a new program for two-stage operation was not possible because the outdoor temperature was too warm.

A second challenge with controlling the CCHP was determining when to vary the heat output to the building. The zone temperature would go below the set point and a call for heat would be given. The CCHP would kick on in single-stage mode with a fixed compressor speed. If the zone temperature stayed below the set point, the speed would increase to increase the heat output of the CCHP to the building. At some point the top speed is reached and switching into two-stage is required for additional heating capacity. The decision for how long to continue in single stage before switching into two-stage was done with a proportional-integral derivative (PID) controller. The details of all the control logic can be seen in Appendix B of the final report. The gains were estimated at first and modified during testing to reach reasonable operation. Robust testing of all the CCHP controls, single-stage and two-stage heating, defrost, oil management, etc. were needed to reach an optimum performance. These improvements had a strong impact on the overall efficiency of the system.

8.5 SUMMARY

The field demonstration encountered unexpected obstacles. However, the field testing made great strides to identifying key problems and implementing solutions. Below are several recommendations that are being considered for new development that is already underway.

- Select a suction pipe diameter that provides a high enough velocity to return oil back to the compressor or implement a similar programming strategy in which the compressor periodically speeds up to provide a sufficient velocity to return oil back the compressor.
- Utilize crankcase heaters regardless of the compressor’s location.

- Utilize a single oil separator and have the oil line return to the inlet to the accumulator.
- Pre-charge accumulator with compressor oil until the oil lever is higher than the oil orifice.
- Utilize a refrigerant inventory management device/method.
- Use a commercially available and robust electronic expansion valve that can tolerate saturated-liquid or slightly two-phase refrigerant.
- Optimize the CCHP controls by running extensive tests on modulating the heat output.

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APPENDIX A

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